MAPPING BURNED AREAS AND ESTIMATING FIRE EMISSIONS OVER THE CANADIAN BOREAL FOREST

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ABSTRACT

A comprehensive investigation of Canadian boreal forest fires was conducted using NOAA-AVHRR imagery. Algorithms were developed to (1) detect active forest fires, (2) map burned areas on daily and annual basis, and (3) estimate fire emissions based on burned area and Canadian Forest Service fuel consumption models. The algorithms lay the foundation for an operational fire emissions calculator.

Keywords: boreal forest, fire, burned area, emissions

INTRODUCTION

The boreal forest zone accounts for about 25% of global forest area. In Canada the boreal forest makes up the largest biome, with 75% of all wooded land and 67% of exploitable closed forest being classified as boreal forest (Weber and Stocks, 1998). On average, approximately 10,000 wildfires occur in Canada each year, burning over 2.5 million ha. These fires emit significant quantities of trace gases (e.g., CO^2, CO and CH^4) and smoke aerosol into the atmosphere, both of which influence the earth's radiation budget.

To estimate the potential impacts of forest fire on environment and climate, techniques are required to accurately determine the extent of burning. Burned area estimates can be combined with fuel consumption models and emission factors from the literature to quantify fire emissions. Due to the widespread extent and remoteness of boreal fires, satellite remote sensing is particularly well suited to this task.

The purpose of this paper is to describe boreal fire algorithms produced by scientists from the Canada Centre for Remote Sensing (CCRS) and industry. Algorithms were developed to detect active fires, map daily and annual burned areas, and compute fire emissions based on NOAA-AVHRR imagery. The emissions model relies on output from the burn mapping algorithms, while burned area requires hotspot location information from the fire detection algorithm. Together, these interrelated algorithms provide a framework for estimating daily fire emissions across Canada.

ACTIVE FIRE DETECTION

A boreal forest fire detection algorithm was developed that exploits multi-channel information from AVHRR imagery (Li et al., 1998a). The algorithm consists of two major steps: identifying potential fire pixels using their strong thermal response in the mid-infrared channel (3.7 µm), then removing false fires using a series of threshold tests (Figure 1). Tests were optimized using a 1,200 by 1,200 km training data set to detect

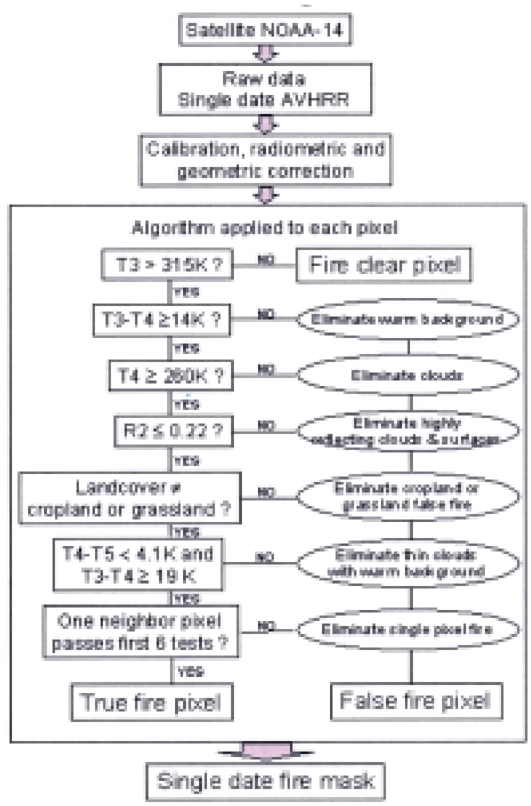

Figure 1. Flowchart of processing steps required for the NOAA-14 fire detection algorithm.

most real fires, while eliminating as many false fires as possible. Histogram analyses of reflectance and brightness temperature corresponding to burning and non-burning pixels were used to optimize threshold values.

The hotspot algorithm was applied to archived single-date AVHRR composites for the years 1994-1997, yielding a daily fire mask for all of Canada. In summer, 1998, the algorithm was applied operationally. Images showing active fires and smoke were generated within 24 hours of satellite reception, and sent to media and provincial and federal fire management agencies. Beginning in 1999, daily Canada-wide hotspot maps are published online as part of the CCRS/Canadian Forest Service Fire Monitoring, Mapping, and Modeling System (Fire M3; http://fms.nofc.cfs.nrcan.gc.ca/FireM3/).

The hotspot locations for 1995 were compared to digital fire surveys provided by provincial fire agencies. The algorithm was found to detect the vast majority (> 90%) of fires larger than 300 ha. Within individual burns, however, the distribution of hotspots is patchy due to limited satellite revisit frequency and obscuring by smoke and cloud (Figure 2). Consequently, the cumulative area of all hotspot pixels detected during each summer was, on average, about 30% less than official survey estimates. To account for these missed burned patches, new burned area mapping techniques are being developed.

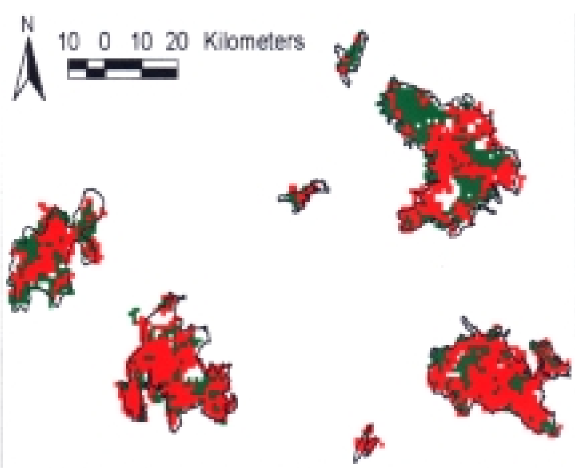

Figure 2. Region in Saskatchewan that was subject to several large burns in 1995. Hotspots detected using the fire detection algorithm are shown in red. Burned areas not detected as hotspots but mapped using HANDS burn mapping algorithms are shown in green. The outer burn boundaries mapped by the province are also shown.

BURNED AREA MAPPING

Satellite change detection techniques have been employed in an attempt to provide more accurate estimates of burned area than is possible from hotspot detection. One such technique involves computing the difference between anniversary date (spring or fall) NDVI composites, then establishing a threshold suitable for separating new burns (Kasischke and French, 1995, Li et al., 1998b). Although NDVI differencing can successfully discriminate most burned areas, it is also prone to detecting false burns due to NDVI decreases unrelated to fire (e.g., from drought, harvesting, or cloud contamination). Furthermore, it is difficult to derive a threshold that is effective over large, heterogeneous regions such as the Canadian boreal forest.

To overcome these problems, new burn mapping techniques are being developed at CCRS that exploit hotspot location information from the fire detection algorithm. One technique, abbreviated HANDS (Hotspot and NDVI Differencing Synergy), combines hotspots with differencing of anniversary date NDVI composites to provide an annual map of burn areas (Fraser et al., 1999). The algorithm uses annual hotspot locations to derive a spatially variable difference threshold for separating burned areas (Figure 3). A coarse, regional difference threshold is first applied, followed by a more restrictive local threshold. The local threshold is derived for individual burn patches, which are isolated using GIS clumping techniques.

The mapping technique was applied to Canadian forest for the 1995 and 1996 fire seasons. National burned area was calculated to be 6.8 million ha in 1995 and 2.0 million ha in 1996, comparing favorably to Canada Forest Service estimates of 7.1 and 1.9 million ha, respectively. Moreover, at local scales, HANDS burns closely corresponded to individual burn polygons derived from aerial surveys (Figure 2).

In addition to annual mapping of burned areas (i.e., HANDS), we are developing a technique for near real-time, daily mapping of burns. This method employs single date AVHRR imagery, and uses current hotspots as seeds for a burn growth algorithm. Burned pixels are iteratively “grown” from hotspot locations if they satisfy three conditions:

1. Joined to a hotspot or previously identified burned pixel.

2. Not cloudy, based on a thermal infrared (channel 4) threshold.

3. Elevated mid-infrared (channel 3) signal with respect to background.

Tests #2 and #3 are specifically designed to permit mapping of burned areas that are covered by smoke plumes.

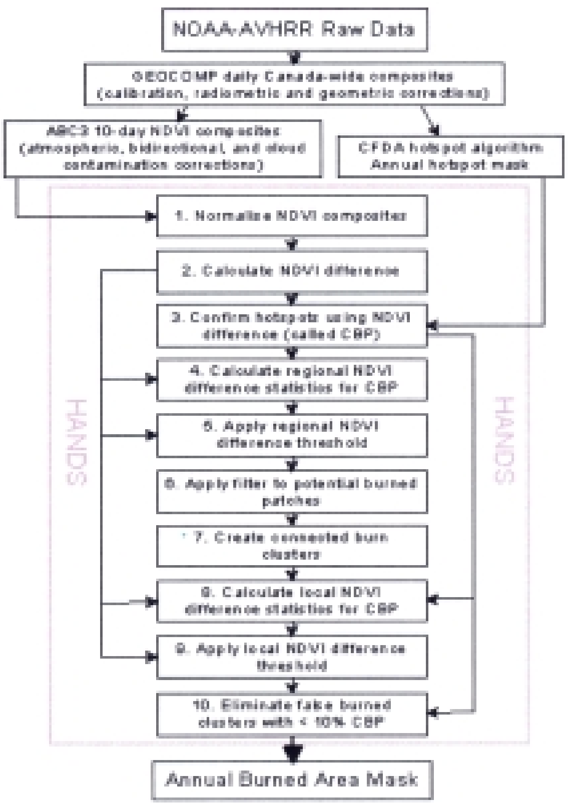

Figure 3. Flowchart of processing steps required for the HANDS burn mapping algorithm.

ESTIMATING FIRE EMISSIONS

A spatially and temporally explicit model was developed to estimate forest fire emissions. The model consists of three components: daily burned area mapping, fuel consumption estimation, and fire emissions estimation. A massive 1998 forest fire that occurred in the Virginia Hills in central Alberta (116º07'W, 54º38'N) served as a case study. The study area, lying within the Lower Foothill of the Boreal Forest region, comprises hardwood, softwood, and mixedwood stands, clear-cuts, regeneration, numerous regenerating burns, wetlands, small lakes, and seismic survey lines. A fire was detected in the area on May 3, 1998, which spread rapidly due to extreme fire weather conditions. The official estimate of the area damaged is 1,541 km^2 (154,094ha), the majority of which burned between May 4-5 before dying out on May 20.

Daily Burned Area Mapping

The near real-time burned area algorithm described in the previous section was applied to daily AVHRR images corresponding to the 18 day burning period (May 3-May 20). Figure 4 shows the resulting cumulative burned area for each day. Burned pixels identified on a given day are then linked to current fire weather data in order to estimate fuel consumption.

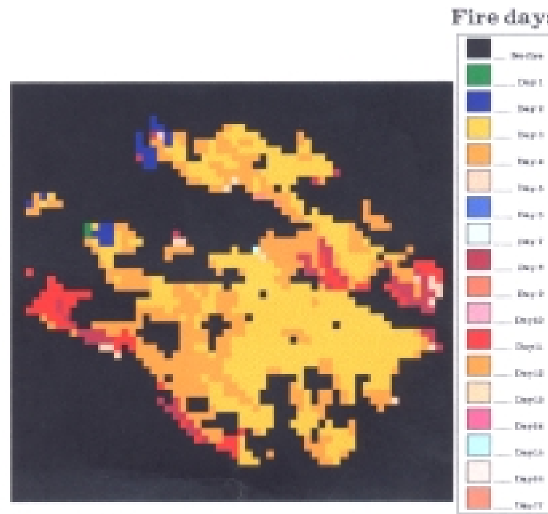

Figure 4. Daily cumulative burned area for the Virginia Hills fire.

Fuel Consumption Estimation

Fuel consumption for the Virginia Hills fire was computed using The Canadian Forest Fire Danger Rating System, consisting of a Fire Weather Index (FWI) System (Van Wagner, 1987) and Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992). The FWI system, referring primarily to a standard pine fuel type, calculates fuel moisture codes and fire behavior indexes based on daily weather. The FBP system provides separate estimates of fire behavior for 16 fuel types based on FWI and topography. The primary outputs of FBP system are rate of spread (m/min), fuel consumption (kg/m2), and fire intensity (kW/m). Three fuel types within the study area were mapped using a 1995 land cover classification derived from AVHRR imagery (Cihlar and Beaubien, 1998).

Total fuel consumption (TFC) includes surface fuel consumption (SFC) and crown fuel consumption (CFC). The moisture codes and indices of FWI system, fuel types, and topography determine how much surface fuel is consumed, whether a crown fire occurs, and what fraction of the crown fuel is consumed [2]. Figure 5 shows modeled fuel consumption for the Virginia Hills fire. Figure 6 presents a flowchart of the fuel consumption and fire emissions model.

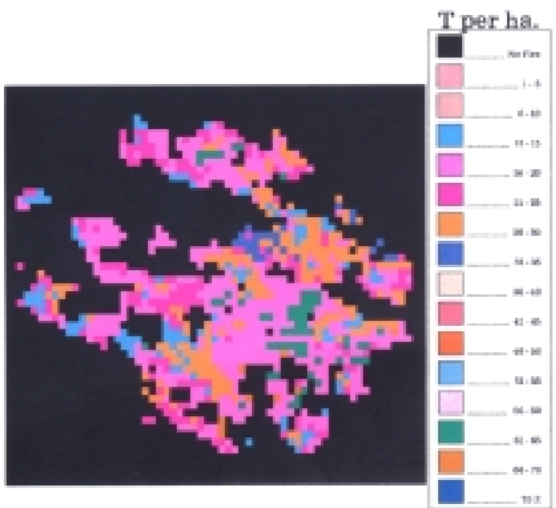

Figure 5. Total fuel consumption (crown and surface fuels) for the Virginia Hills fire.

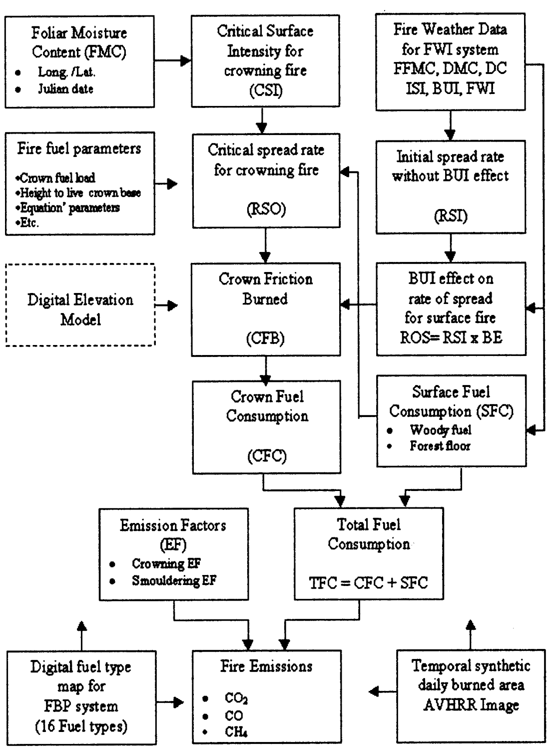

Figure 6. Data flowchart of model for fuel consumption and fire emissions.

Fire Emissions Estimates

Emissions from the fire were estimated on a temporally explicit basis for each affected pixel using the following equation.

Daily fire emission (t) =

Σ Fuel consumption (kg/m^2) x Pixel area (km^2) x Emission factor (g/kg),

Emission factors, which relate the emission of gas x (g) to fuel consumption (kg), were obtained from Cofer et al. (1998). The emission factors were derived from smoke samples collected during the International Crown Fire Modeling Experiment in Northwest Territories, Canada.

Table 1 below summarizes fuel consumption and fire emissions from the Virginia Hills fire for three important trace gasses. Figure 7 presents spatially explicit CO^2 emissions for the fire.

Type of burning	Pixels	Avg. fuel consumpt -ion (t/ha)	Emissions from fire (megatons)		
			CO_2	CO	CH_4
Surface	994	20.4	2.7743	0.2873	0.0103
Crown	716	3.5	0.3716	0.0272	0.00007
Total	994	23.9	3.1459	0.3145	0.011

Table 1. Estimated fuel consumption and emissions.

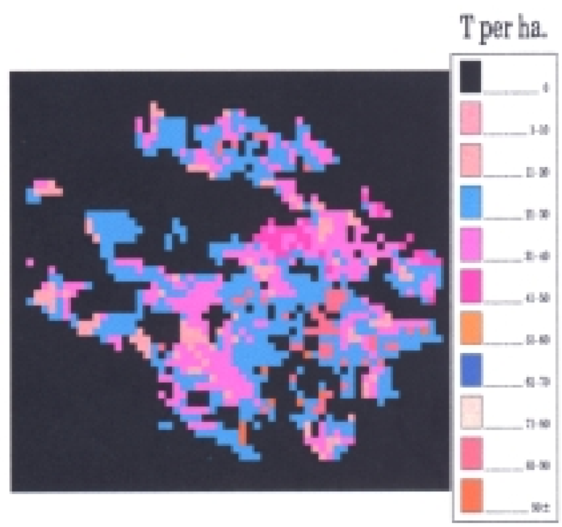

Figure 7. Spatially explicit CO^2 emissions for the Virginia Hills fire.

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